

Ka-Band Unit-Cell for Tunable Metasurfaces

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Abstract—This paper reports a tunable Ka-Band metasurface unit-cell design integrated with commercial off-the-shelf varactor. A simple E-shaped unit-cell geometry is proposed with only a single tuning element with capacitance variation from 0.3 pF to 2.2 pF, operating at 40 GHz. The unit-cell is optimized for a low-cost FR4 substrate without any stringent signal-to-gap tolerances, making this design, an optimum choice for prototyping larger surfaces. An equivalent circuit model is presented in addition to the performance validation using full wave 3D EM simulations. The proposed cell offers more than 300° phase shift with a reflection amplitude of 0.2 for low-cost, one element per unit-cell solution for wireless coverage enhancement.

I. INTRODUCTION

The field of metasurface technology has revolutionized the landscape of electromagnetic and optical device engineering, offering unparalleled control over wave propagation [1]. In the realm of high-frequency applications, especially within the Ka-Band spectrum, the demand for advanced metasurface designs is rapidly escalating. This frequency range, occupying a significant portion of the microwave spectrum, is pivotal in numerous applications, ranging from wireless communications to radar systems [2]. However, the design of metasurfaces in this band poses unique challenges, chiefly due to the stringent requirements for phase control and amplitude modulation [3], [4]. Addressing these challenges, our paper focuses on the design and optimization of a tunable Ka-Band unit-cell.

Moreover, the advancements in the unit-cell design play a pivotal role in enhancing radio coverage, especially in challenging environments. The unique attributes of our Ka-Band unit-cell, primarily its wide phase shift range and low reflection magnitude, contribute to improved signal penetration and reduced interference. These characteristics are essential for extending radio coverage in urban landscapes and remote areas where signal attenuation and multipath fading are prevalent challenges. By enabling more efficient wavefront manipulation, our unit-cell design sets a new precedent for developing robust communication systems that can maintain high-quality signal transmission over greater distances and through various obstacles. This enhancement in radio coverage not only broadens the operational scope of communication systems but also promises significant improvements in the reliability and accessibility of wireless networks across diverse geographical terrains.

Metasurfaces assisted wireless coverage enhancements are promising for future wireless networks as shown in Fig. 1. The EM waves can reflect off metasurfaces to provide coverage to the user equipment (UE) which are in the shadow region or wherever a line-of-sight (LoS) path can't be made directly between the base station and the UEs. The metasurfaces with

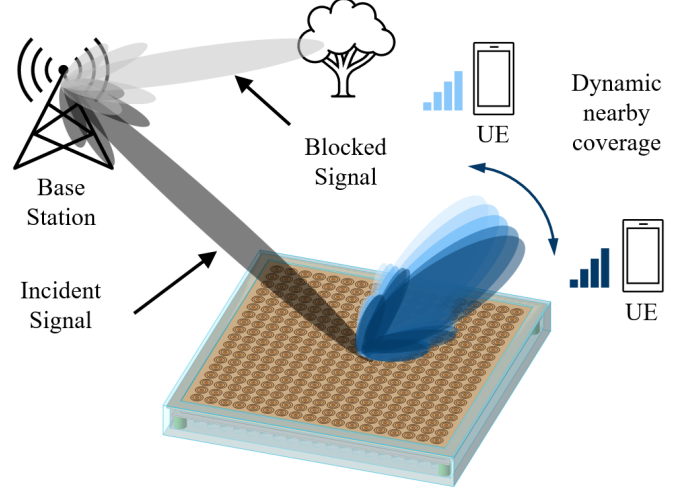


Fig. 1. Tunable metasurfaces for enhancing wireless coverage

tuning capability can steer the beam with certain array gain, pivotal for 5G-Advanced and 6G communications.

II. DESIGN AND VALIDATION

The unit-cell serving as an elemental design is proposed to operate at Ka-Band with more than 4 GHz bandwidth around 40 GHz center frequency. The 3D view of the proposed unit-cell is shown in Fig. 2 and the layout of the cell with design dimensions is shown in Fig. 3. The unit-cell is designed and optimized to avoid any stringent trace or gap spacing, which lower the fabrication costs and complexities. The cell consists of top metallization layer showing cascaded back-to-back connected E-shaped geometry. In this design, up to 5% of the trace/gap fabrication tolerance are accounted for without having more than 1% performance difference. This design only requires two layers connected using interconnects and the bottom metallization plane serves as bias layer in conjunction with the RF ground.

The unit cell is made up of a conducting scatterer comprising two E-shaped patches, interconnected by a commercial off-the-shelf surface mount tuning varactor diode. The geometrical parameters of the unit cell, namely $w = 2$ mm, $w_1 = 0.2$ mm, $L = 2$ mm, $l_1 = 0.7$ mm, $th = 0.035$ mm, $g = g_1 = 0.2$ mm, and $h = 2.4$ mm are chosen to provide optimum phase and amplitude range of the reflected waves. The metasurface is designed on low-cost FR4 laminate with thickness 2.4 mm and $\epsilon_r = 4.3$.

Despite operating with a relatively low reverse voltage, the mentioned diode exhibits a specific high capacitance, making it well-suited for providing a large tuning range at mmWave. In the absence of this diode on the scatterer, the reflected wave

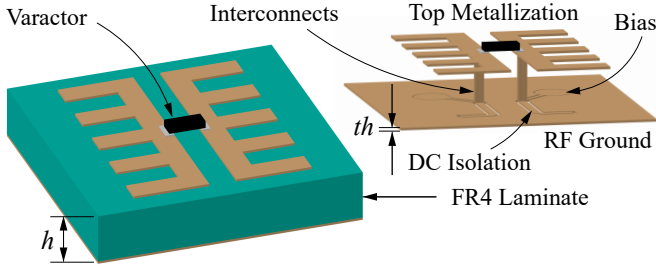


Fig. 2. 3D model of the proposed Ka-Band unit-cell with back-to-back connected E-shaped conductors connected using a tunable commercial varactor.

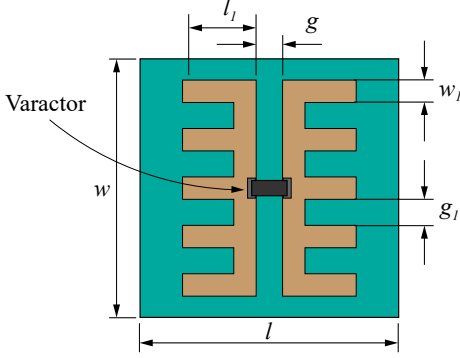


Fig. 3. Top view of the unit-cell with various design dimensions.

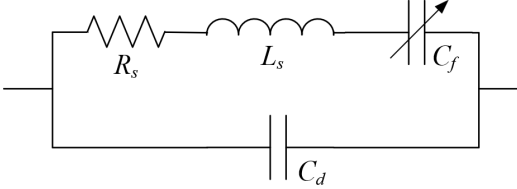


Fig. 4. Equivalent circuit model of the unit-cell.

maintains a constant phase compared to the incident waves. However, by adjusting the reactance value of the varactor, a manipulated phase is added to this constant phase, resulting in a customized range of phase without any modifications to the physical properties of the scatterer.

The equivalent circuit of the tunable components is shown in Fig. 4. It is characterized by a tunable capacitance C_f with range from 0.3 pF to 2.2 pF at 40 GHz. The parasitic inductance and capacitance of the package is $L_s = 0.7$ nH and $C_d = 0.15$ pF, with a series resistance of $R_s = 1.8 \Omega$.

By biasing the varactor, a significant variation range of 326° is achieved for the reflection phase within a wide operating region of 4 GHz.

The full wave 3D EM-simulated reflection magnitude and phase of the unit-cell for various capacitance values of the varactor is illustrated in Fig. 5, and Fig. 6, respectively. The simulations are carried out from 35 GHz to 45 GHz and the unit-cell performs relatively well in the mid 4 GHz band. This proposed geometry offers a low-cost solution to implement

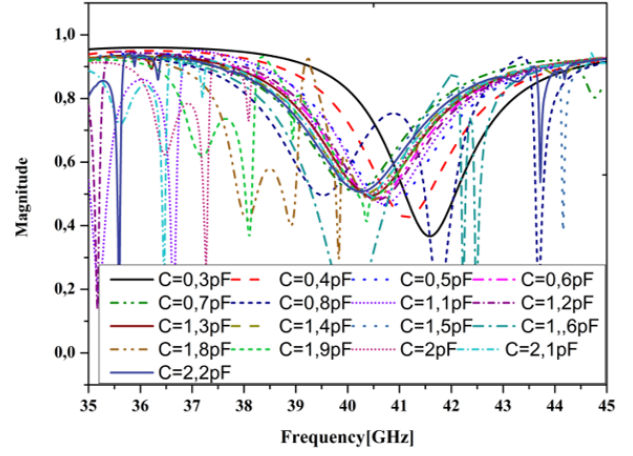


Fig. 5. Magnitude response of the unit-cell.

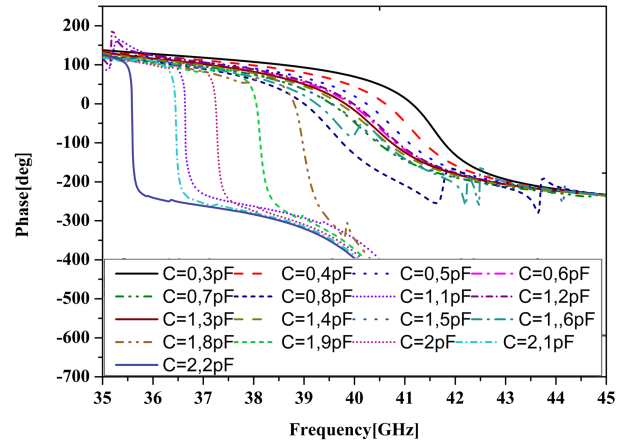


Fig. 6. Phase response of the unit-cell.

tunable metasurfaces with only a single tuning element for wireless coverage enhancement.

III. CONCLUSION

A Ka-Band unit-cell is proposed with the design optimized for low-cost FR4 substrate and design dimensions that can tolerate a large fabrication variations without limiting the performance. The presented structure only requires a single tuning element, further reducing the bias complexity and multi-layer requirements.

REFERENCES

- [1] J. Y. Dai et al., "Wireless Communication Based on Information Metasurfaces," *IEEE Trans. Microw. Theory Techn.*, vol. 69, no. 3, pp. 1493-1510, Mar. 2021.
- [2] E. Martini and S. Maci, "Theory, Analysis, and Design of Metasurfaces for Smart Radio Environments," *Proc. IEEE*, vol. 110, no. 9, pp. 1227-1243, Sept. 2022.
- [3] D. V. Q. Rodrigues and T. Singh, "Efficient Power Allocation Strategies in Hybrid Active-Passive Reconfigurable Intelligent Surfaces," *IEEE Commun. Lett.*, vol. 28, no. 1, pp. 113-117, Jan. 2024.
- [4] O. Yildiz, M. Alavirad and T. Singh, "Investigation and Optimization of Secrecy Capacity for Intelligent Reflective Surfaces-Assisted Secure mmWave Indoor Wireless Communication," in *Proc. IEEE Radio and Wireless Symposium (RWS)*, Las Vegas, NV, USA, 2023, pp. 1-3.